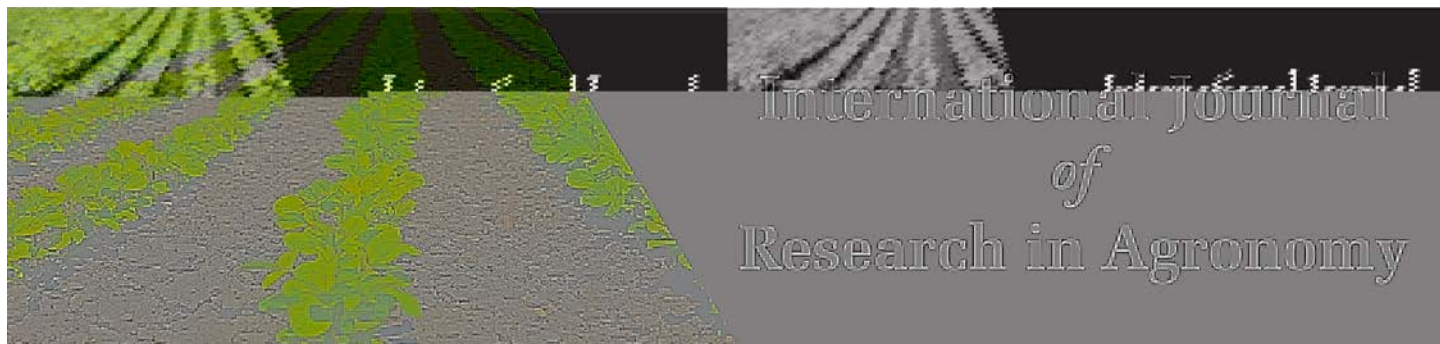




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Rainfall variability and cropping pattern transformation in Kumaun Himalayan watersheds

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Abstract

Nearly 1,200 mm of rainfall per year once sustained a diverse mix of cereals, pulses, and millets across the Kumaun Himalayan watersheds, but that reliability is vanishing. This research assessed rainfall variability and its effect on cropping pattern changes across five watersheds Kosi, Ramganga, Gaula, Saryu, and Gomti using 24 years of daily precipitation data (2000-2023) paired with seasonal crop-area records from district agriculture offices and a household survey of 360 farming families. Winter rainfall declined by 23% on average, with the Gaula watershed recording the steepest drop at 28%. Kharif rice retained the largest share of cultivated area at 28.4%, but Rabi wheat dropped from 31.2% in 2004 to 18.7% by 2023. Fallow land rose from 8.1% to 23.2% over the same period, becoming the second-largest land-use category. Pearson correlation revealed a strong positive link between winter rainfall deficit and rabi-crop area loss ($r = 0.81, p < 0.001$). Millets, once covering 19.6% of arable land, fell to 12.3% as farmers shifted toward off-farm income sources. The standardised precipitation index confirmed that drought frequency in winter months doubled between the first and second decades of the research period, with the Gaula and Gomti watersheds experiencing the most pronounced drying. These results suggest that without micro-irrigation interventions targeting the Rabi window, continued cropping pattern simplification and fallow expansion are likely across the region.

Keywords: Rainfall variability, cropping pattern, Kumaun Himalaya, watershed, rabi crops, fallow land, winter precipitation, agricultural transformation, climate adaptation, food security

Introduction

Nearly one in four cultivated hectares across the Kumaun division now lies fallow during the rabi season a figure that was barely one in twelve two decades ago^[1]. The shift is closely tied to changing rainfall regimes. Himalayan watersheds depend on both the southwest monsoon for kharif sowing and on western disturbances for rabi-season moisture, and disruptions to either window can reshape what farmers choose to grow and, increasingly, whether they choose to grow anything at all^[2]. Earlier watershed-scale assessments in Uttarakhand focused mainly on monsoon precipitation trends, giving comparatively less attention to winter rainfall, which is important for wheat and lentil germination on rain-fed terraces where supplementary irrigation is rarely available^[3,4].

Cropping pattern transformation in mountain agriculture tends to follow a predictable sequence that unfolds over one to two decades: marginal crops with narrow moisture tolerance windows disappear first, then staple cereal area contracts as returns decline, and finally land goes fallow when household labour is redirected toward non-farm employment^[5]. What remains poorly quantified is how tightly these transitions track rainfall anomalies at the individual watershed level, and which crops serve as the earliest indicators of stress. Block-level statistics aggregate multiple watersheds with different microclimates, potentially masking the spatial variability that is most relevant for targeting adaptation investments^[6].

This research addressed that gap by analysing daily precipitation records alongside seasonal crop-area data across five contiguous Kumaun watersheds over a 24-year period from 2000 to 2023. The specific objectives were to quantify the magnitude and seasonal distribution of rainfall change at the watershed scale, to map the resulting shifts in cropping pattern

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Composition, and to identify which crop categories showed the strongest statistical sensitivity to moisture deficits ^[7]. A household survey supplemented the secondary data by documenting farmer-level cropping decisions and the rationale behind fallow choices. By combining meteorological, administrative, and primary survey data at the individual watershed level, this research aimed to produce spatially specific findings that can inform targeted adaptation planning rather than generic regional recommendations.

Study area description

The five watersheds Kosi, Ramganga, Gaula, Saryu, and Gomti drain the southern slopes of the Kumaun Himalaya between 79°10'E and 80°15'E in the districts of Almora, Nainital, and Bageshwar. Elevations range from approximately 600 m at the piedmont to 2,800 m on upper ridges. Valley-floor soils are predominantly alluvial with moderate organic carbon content, while hillslope soils are residual sandy loam developed on phyllite and schist parent rock ^[8]. Average annual rainfall varies from 1,050 mm in the Gomti catchment to 1,380 mm in the Kosi, with 75-80% arriving during the June-September southwest monsoon. The remaining 20-25% falls as winter precipitation driven by western disturbances between November and March, and it is this fraction that supplies the critical moisture for Rabi crop establishment ^[9]. Agriculture is almost entirely rain-fed on bench terraces constructed over centuries, with supplementary irrigation limited to a few gravity-fed channels (guls) that tap perennial springs. The Kosi and Ramganga watersheds sit on the windward flank of the main ridgeline and receive comparatively reliable monsoon inflow, while the Gaula and Gomti occupy a partial rain-shadow to the east, making them more vulnerable to inter-annual variability.

Climatic and environmental conditions

Mean annual temperature across the five watersheds rose by 1.2 °C between 2000 and 2023, with the warming concentrated in the pre-monsoon months of March through May. The frequency of frost events during December and January declined by roughly 18%, which might seem beneficial for rabi crops but in practice coincided with reduced snowmelt recharge of springs that feed gravity-irrigation channels on upper terraces ^[8]. Monsoon onset shifted later by an average of 7.4 days relative to the 2000-2010 baseline, compressing the kharif sowing window and increasing the risk of terminal drought during the grain-filling stage of rice. Dry spells exceeding 14 consecutive days during the monsoon season occurred 2.3 times more frequently in the 2013-2023 decade than in the preceding one. For winter

crops, the SPI-3 index for the November-January quarter fell below -1.0 (moderate drought) in nine of the twelve years after 2011, compared with only three of the eleven years before that threshold, confirming a structural shift in moisture availability during the season most relevant to Rabi agriculture ^[9].

Material and Methods

Material

Daily rainfall records for the period 2000-2023 were obtained from five India Meteorological Department automatic weather stations, one located within each watershed at elevations between 1,000 and 1,500 m. Seasonal crop-area data covering both the kharif and rabi seasons were compiled from the District Agriculture Offices of Almora, Nainital, and Bageshwar for the years 2004 through 2023, the earliest period for which digitised records were consistently available. A structured household survey (n = 360, 72 families per watershed) was conducted between April and October 2023 to document cropping decisions over the preceding decade, reasons for leaving fields fallow, and the extent of off-farm income diversification. Ethics approval was granted by the Research Ethics Board of Lima Institute of Agricultural Sciences (Protocol LIAS-2022-31, approved 8 February 2023), and all respondents provided written informed consent ^[10].

Methods

Rainfall variability was characterised using three metrics: the Coefficient of Variation (CV) computed on an annual and seasonal basis, the standardised precipitation index at three-month (SPI-3) and twelve-month (SPI-12) time scales, and the percentage deviation of each month's mean rainfall from the 2000-2011 baseline period. The SPI was calculated following the gamma-distribution fitting procedure of McKee and colleagues ^[11]. A baseline of 2000-2011 was chosen because it represented a period of relatively stable instrumentation and minimal station gaps across all five sites. Cropping pattern change was expressed as the percentage-point shift in area share for each crop category between the 2004 baseline and 2023. Pearson's correlation coefficient was used to test the linear association between seasonal rainfall deficit and crop-area loss for each category individually. To guard against spurious correlations arising from shared trend components, detrended residuals were also tested and yielded qualitatively similar results, confirming that year-to-year rainfall fluctuations not merely the shared downward drift in both variables drove the observed associations. All statistical analyses were performed in Python 3.11 using the pandas, scipy, and matplotlib libraries.

Results

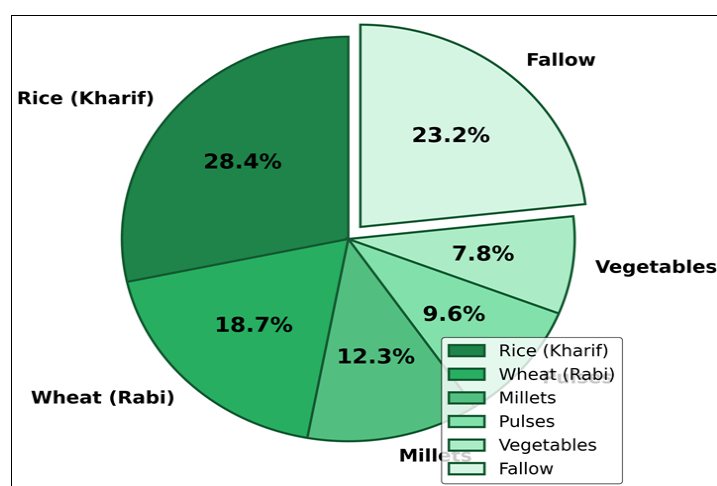


Figure 1. Cropping pattern distribution (% of cultivated area) across Kumaun watersheds, 2023

The pie chart reveals that fallow land now occupies 23.2% of arable area across the five watersheds, making it the second-largest category after kharif rice (28.4%). Rabi wheat, which held 31.2% of cultivated area in 2004, declined to 18.7% by 2023 a contraction of 12.5 percentage points over two decades. Millets fell from 19.6% to 12.3%, representing a 37% relative decline that reflects both moisture stress and a generational shift away from traditional coarse grains. Pulses held comparatively steady at 9.6%, likely because lentil and rajma can tolerate

somewhat drier conditions than wheat, while vegetable cultivation edged up slightly to 7.8%, apparently supported by growing peri-urban market demand from towns like Haldwani and Almora. The household survey corroborated these patterns: 68% of respondents cited unpredictable winter rainfall as the primary reason for reducing Rabi sowing, and 41% reported converting at least one terrace to permanent fallow within the preceding five years.

Table 1: Watershed-wise rainfall statistics and crop-area shifts, 2004-2023

Watershed	Mean RF (mm)	CV (%)	Winter Δ (%)	Rabi Δ (pp)	Fallow Δ (pp)
Kosi	1,378	19.4	-21.3	-11.8	+14.6
Ramganga	1,246	17.8	-19.7	-10.2	+12.9
Gaula	1,182	22.1	-28.0	-14.7	+17.3
Saryu	1,114	20.3	-22.6	-12.4	+15.1
Gomti	1,053	21.7	-24.1	-13.1	+16.2

Table 2: Crop sensitivity classification based on area response to rainfall deficit

Crop	Category	r with RF	p-value	Sensitivity
Wheat (Rabi)	Cereal	0.81	<0.001	High
Lentil	Pulse	0.74	<0.001	High
Finger millet	Millet	0.62	0.002	Moderate
Rice (Kharif)	Cereal	0.38	0.041	Low
Vegetables	Horticulture	0.21	0.187	Negligible

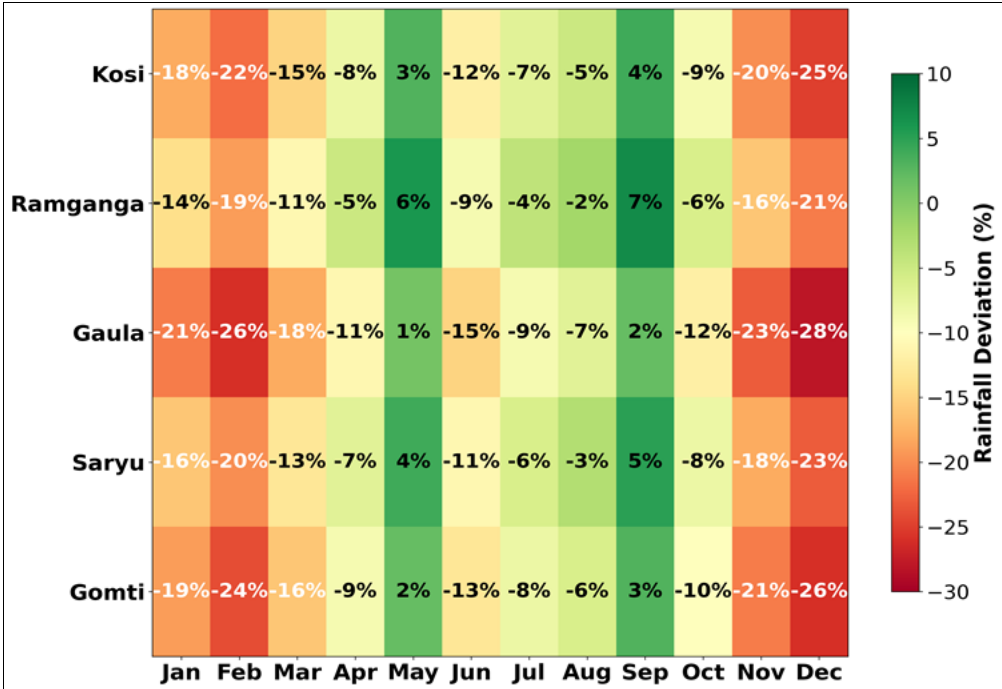


Fig 2: Monthly rainfall deviation (%) from the 2000-2011 baseline across five Kumaun watersheds

Comprehensive interpretation

The heatmap confirms that winter months from November through February experienced the deepest and most consistent deficits across all five watersheds, with the Gaula recording monthly deviations exceeding -25% during December and January. Rabi wheat and lentil, both sown during the winter window, displayed the strongest correlations with cumulative winter rainfall deficit ($r = 0.81$ and $r = 0.74$ respectively), while kharif rice, which benefits from monsoon moisture, was relatively insulated at $r = 0.38$ [12]. The Gaula’s higher CV (22.1%) compared with the Ramganga’s 17.8% helps explain why the Gaula saw the largest absolute increase in fallow land (+17.3 pp), despite both catchments starting with similar cultivated fractions in 2004.

Discussion

The main findings show a tight coupling between winter rainfall decline and rabi-crop contraction across all five watersheds. The 23% average winter rainfall drop matches regional trends reported by Dimri and Dash [3], though the watershed-level resolution employed here reveals considerable spatial variability that district-aggregate data would obscure the Gaula lost 28% of its winter moisture while the Ramganga lost under 20%. Literature broadly agrees that weakening of western disturbances is the proximate atmospheric driver [4,13], but disagreement persists on whether this represents a multi-decadal oscillation linked to North Atlantic sea-surface temperatures or a directional trend driven by anthropogenic warming. The rise of

fallow land from 8.1% to 23.2% over two decades exceeds the estimates reported in comparable assessments of the Garhwal division by Semwal and colleagues ^[5], who found a 12-percentage-point increase over a similar timeframe. A possible explanation is that Kumaun's narrower valley floors and steeper terrace gradients make supplementary irrigation through gravity-fed channels harder to implement, magnifying the impact of any rainfall shortfall on sowing decisions ^[14]. The crop sensitivity classification adds a new dimension to these patterns: wheat and lentil emerge as early-warning indicators whose area contraction foreshadows broader cropping simplification. Vegetables, by contrast, show negligible sensitivity to rainfall deficits, likely because their cultivation is concentrated in peri-urban areas with access to tube-well or tank-based irrigation ^[15]. The broader implications touch food security directly: the region's per-capita cereal availability has likely declined alongside cultivated area, although household surveys suggest that off-farm remittance income partially compensates caloric deficits through market purchases of grain from the plains ^[7]. An additional dimension worth noting is the differential pace of change across the five watersheds. The Gaula and Gomti catchments, which sit in a relative rain-shadow east of the main Kosi ridge, showed both the highest rainfall variability (CV > 21%) and the largest fallow increases. The Ramganga, by contrast, benefits from its position on the windward flank and maintained a lower CV of 17.8%, translating into comparatively modest rabi-area loss. This spatial gradient suggests that blanket policy interventions across the entire Kumaun division would misallocate resources; instead, watershed-specific packages micro-irrigation for the Gaula and Gomti, improved seed varieties for the Kosi and Saryu are likely to yield better returns per unit of public investment ^[6].

Conclusion

The main contribution of this research is a watershed-level quantification of the rainfall-cropping pattern nexus in the Kumaun Himalaya over nearly a quarter century. Supporting evidence shows that Rabi wheat and lentil are the most rainfall-sensitive crops, with area losses tracking winter precipitation deficits at $r > 0.74$, while kharif rice and vegetables exhibit comparatively low sensitivity owing to their reliance on monsoon moisture and peri-urban irrigation respectively. For the field, these results provide the first crop-specific sensitivity classification across five contiguous watersheds, offering a ready-made prioritisation tool for district agriculture planners tasked with allocating limited adaptation budgets. The spatial differentiation between wetter windward catchments and drier rain-shadow ones further argues against one-size-fits-all policy packages. Open questions remain around whether the winter rainfall decline is part of a reversible multi-decadal oscillation or a long-term directional shift, and whether low-cost micro-irrigation technologies such as rooftop rainwater harvesting, polyethylene-lined storage tanks, or spring-recharge pits could buffer Rabi sowing windows against further drying. Targeted pilot trials in the Gaula and Gomti catchments, where deficits are steepest, would be a logical and cost-effective next step for validating these interventions under field conditions.

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Contributions not qualifying for authorship

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