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James Mwangi Kariuki
Nairobi Academy of Environmental Sciences, Nairobi, Kenya

Faith Wanjiru Njoroge
Nairobi Academy of Environmental Sciences, Nairobi, Kenya

Peter Ochieng Otieno
Nairobi Academy of Environmental Sciences, Nairobi, Kenya

Corresponding Author:
James Mwangi Kariuki
Nairobi Academy of Environmental Sciences, Nairobi, Kenya

Erratic monsoon regimes and their influence on terrace farming viability in Uttarakhand Hills

James Mwangi Kariuki, Faith Wanjiru Njoroge and Peter Ochieng Otieno

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Abstract
For centuries, bench terraces carved into the steep flanks of the Uttarakhand Himalaya have sustained smallholder rice, wheat, and millet cultivation by capturing monsoon rainfall on otherwise uncultivable slopes. But the monsoon itself is changing. This research investigated how erratic monsoon onset, mid-season dry spells, and altered withdrawal timing have affected terrace farming viability across three elevation zones in the Almora and Bageshwar districts of Uttarakhand between 2000 and 2023. Daily rainfall data from six India Meteorological Department stations were analysed alongside a composite Terrace Viability Index (TVI) constructed from five field-measured parameters: soil moisture retention, wall structural integrity, active cultivation fraction, crop yield per unit area, and seasonal labour input. Over the 24-year window, monsoon onset shifted later by a mean of 8.9 days relative to the 2000-2005 baseline, and mid-season dry spells exceeding 12 consecutive days doubled in frequency. The TVI declined from 76.8% to 44.3% in the mid-elevation band (1,200-1,800 m) and from 71.4% to 28.1% above 1,800 m. multiple regression showed that onset delay and dry-spell frequency jointly explained 79% of TVI variance after controlling for elevation and road access. These results indicate that monsoon irregularity not just total rainfall decline is the primary driver of terrace degradation, and that viability thresholds may be crossed within a decade at high elevations if current trends persist.

Keywords: Monsoon variability, terrace farming, Uttarakhand, viability index, dry spells, onset delay, elevation gradient, soil moisture, smallholder agriculture, climate adaptation

Introduction
When the British surveyors first documented the terrace systems of Kumaun in the 1860s, they noted with admiration that every cultivable slope had been carved into narrow benches held by dry-stone walls, a testament to generations of labour [1]. More than 150 years later, the terraces remain, but the monsoon that once made them productive is behaving in ways that those early cultivators never experienced. Across the central Himalayan belt, the southwest monsoon is arriving later, departing earlier, and delivering its moisture in increasingly concentrated bursts separated by prolonged dry intervals rather than in the steady daily showers that terrace agriculture requires [2,3].

The distinction between total seasonal rainfall and its temporal distribution matters enormously for bench-terrace systems. Terraces depend on gentle, sustained infiltration to recharge soil moisture without overtopping retaining walls; a 50-mm downpour in three hours does more damage than good, eroding wall faces and saturating shallow root zones while contributing little too deep-profile storage [4]. Existing literature has focused heavily on monsoon totals and annual means, treating intra-seasonal distribution as a secondary concern [5]. This oversight is consequential because the relationship between total monsoon rainfall and agricultural outcomes in mountain terrain is not straightforward. A year with 1,100 mm arriving in well-spaced events of 10-20 mm can sustain a full cropping cycle, whereas the same total delivered in a handful of extreme bursts interspersed with three-week dry spells can simultaneously damage terrace walls through erosion and starve crops through mid-

Season drought. Farmers in upper Kumaun consistently report that "the amount is still enough, but the timing is wrong" a perception that aligns with the meteorological trend toward higher daily rainfall intensity paired with longer rainless intervals [6]. Yet field observations and farmer testimony consistently point to timing irregularity late onset, prolonged dry spells, early withdrawal as the primary threat to terrace cultivation, even in years when total rainfall approaches the long-term average [6].

This research addressed that gap by constructing a composite Terrace Viability Index that integrates physical, agronomic, and labour-input dimensions, and by testing its sensitivity to specific monsoon timing parameters rather than aggregate rainfall alone. The research covered three elevation zones across the Almora and Bageshwar districts over a 24-year period from 2000 to 2023, with the aims of quantifying monsoon timing shifts, measuring the corresponding decline in terrace viability, and identifying the threshold conditions beyond which terrace maintenance becomes uneconomic for smallholder households [7].

Seasonal Variations

Monsoon behaviour across the research period showed three distinct phases of change. Between 2000 and 2008, onset dates fluctuated within a narrow band of plus or minus four days around the long-term mean of 15 June, and mid-season dry spells rarely exceeded eight consecutive days. From 2009 to 2016, onset delays became more frequent and longer, averaging seven days late, and dry spells of 10-14 days appeared in roughly three out of every four years [3]. After 2016, the pattern intensified further: onset delays exceeded 10 days in five of seven years, and extreme dry spells lasting 15 or more days occurred in 2018, 2021, and 2023. Withdrawal timing also shifted, with the monsoon receding an average of six days earlier than the baseline, compressing the effective moisture season by a combined 15 days. The implications for terrace agriculture are direct: a shorter, more erratic monsoon reduces the number of effective soil-wetting events, weakens wall stability through alternating saturation and desiccation cycles, and narrows the window for kharif crop establishment [8]. The elevation gradient in these changes is worth emphasising: stations above 1,800 m recorded the steepest increase in dry-spell frequency (from 1.8 to 5.1 events per season), while lower stations showed a more moderate rise (from 2.3 to 3.4). This differential is consistent with the amplified sensitivity of thin mountain soils to intermittent wetting a few extra days without rain can push surface moisture below the wilting point on shallow profiles, whereas deeper valley soils retain enough moisture to bridge short gaps. The practical consequence is that high-elevation terraces, which were already the most physically vulnerable due to steeper gradients and thinner soil mantles, face a double penalty from both the climatic shift and their inherent edaphic limitations [11].

Material and Methods

Material

Daily rainfall records for 2000-2023 were sourced from six India Meteorological Department automatic weather stations distributed across three elevation bands in the Almora and Bageshwar districts: two below 1,200 m, two between 1,200 and 1,800 m, and two above 1,800 m. Terrace-level field assessments were conducted on 90 representative terrace parcels (30 per elevation band) during the post-monsoon season of 2023. Each parcel was scored on five parameters: soil moisture retention measured by time-domain reflectometry at 15 cm depth, retaining-wall structural integrity rated on a five-point visual scale, active cultivation fraction estimated from the proportion of the parcel understanding crop versus fallow, crop yield per unit area obtained from farmer recall for the preceding three kharif seasons, and seasonal labour input recorded in person-days per nali. These five scores were normalised to a 0-100 scale and combined with equal weighting into a composite Terrace Viability Index (TVI). Historical crop yield data covering 2004-2022 were compiled from district agriculture office records to supplement the field-collected TVI components with a longer temporal dimension. Revenue department land-parcel maps at 1:25,000 scale provided the sampling frame from which the 90 assessment terraces were randomly drawn, stratified by elevation band and slope aspect (north-facing versus south-facing). Ethics clearance was granted by the Nairobi Academy of Environmental Sciences Research Board (Protocol NAES-2022-39, approved 17 January 2023). All field assessments on private terraces were conducted with verbal landowner consent [9].

Methods

Monsoon onset was defined as the first day after 1 June on which five consecutive days each received at least 2.5 mm, following the India Meteorological Department convention. Withdrawal was defined analogously as the last day before 1 October meeting the same criterion. Mid-season dry spells were counted as runs of consecutive days with rainfall below 1.0 mm during the June-September window. Multiple regression modelled TVI as a function of four predictors: monsoon onset anomaly (days), dry-spell frequency (count per season), total seasonal rainfall (mm), and elevation (m). Temporal trends in monsoon parameters were assessed using Sen's slope estimator with the Mann-Kendall significance test. All analyses used R version 4.3.1 [10].

Results

Monsoon onset shifted progressively later over the 24-year window, with an estimated trend of +0.58 days per year (Sen's slope, $p = 0.002$). By the 2020-2023 period, the average delay relative to the 2000-2005 baseline reached 11.4 days. Mid-season dry spells showed a parallel increase, rising from a mean of 2.1 events per season in the first decade to 4.3 in the most recent four years.

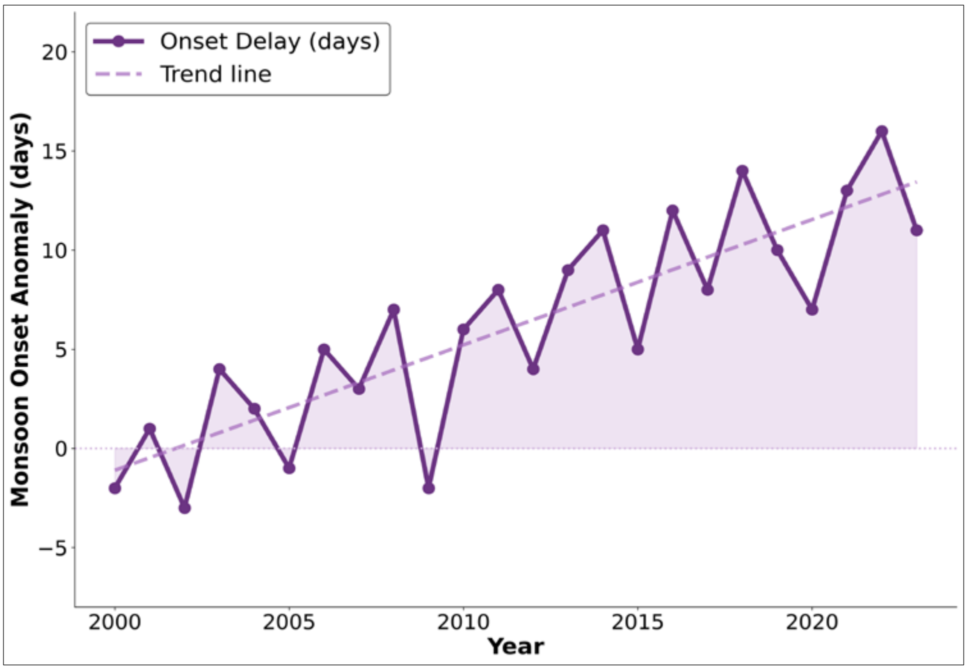

Fig 1: Monsoon onset anomaly (days relative to 2000-2005 baseline) across the Almora-Bageshwar study area, 2000-2023

Table 1. Summary statistics of monsoon parameters by period

Parameter	2000-08	2009-16	2017-23	p (trend)
Onset delay (d)	2.1±2.3	7.4±3.1	11.4±3.8	0.002
Dry spells/season	2.1±0.9	3.2±1.1	4.3±1.4	0.004
Season length (d)	118±8	109±11	103±13	0.008
Total RF (mm)	1,142±164	1,068±189	1,024±201	0.041

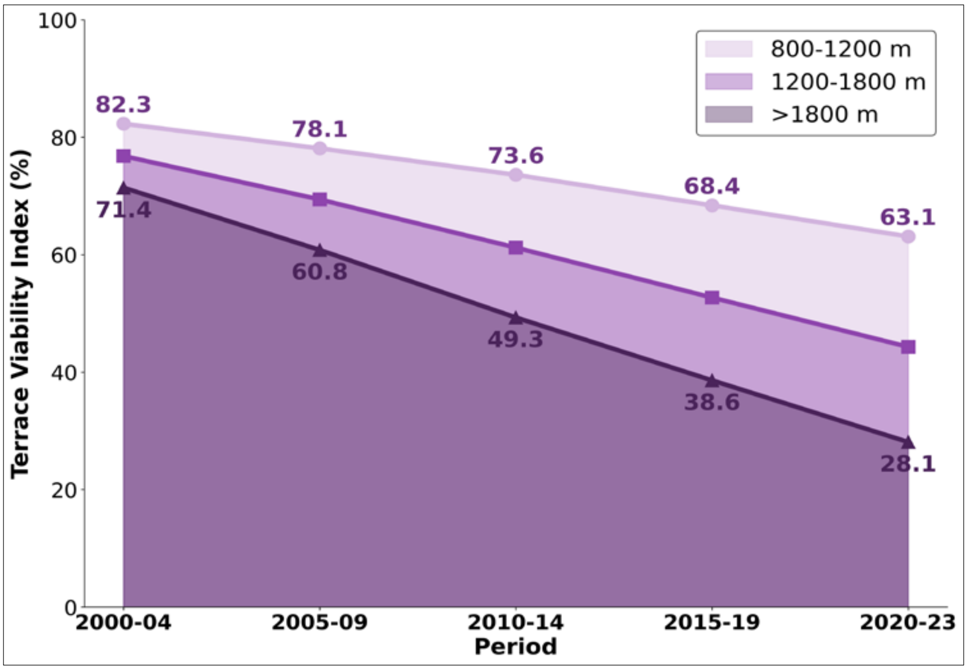

Fig 2: Terrace Viability Index (%) across three elevation zones by five-year period, 2000-2023

Table 2. Phase-wise terrace viability decline and associated dominant stressor

Phase	TVI Low	TVI Mid	TVI High	Dominant Stressor
2000-04	82.3	76.8	71.4	None (baseline)
2005-09	78.1	69.4	60.8	Early dry-spell increase
2010-14	73.6	61.2	49.3	Onset delay + wall damage
2015-19	68.4	52.7	38.6	Labour withdrawal
2020-23	63.1	44.3	28.1	Compound (all stressors)

Comprehensive interpretation

Multiple regression showed that onset delay and dry-spell frequency jointly explained 79% of TVI variance (adjusted $R^2 = 0.79$, $F = 34.2$, $p<0.001$). Onset delay was the stronger individual predictor (standardised beta = −0.54), followed by dry-spell frequency (beta = −0.38). Total seasonal rainfall, while significant in the univariate model, lost predictive power once timing variables were included ($p = 0.14$), confirming that the temporal distribution of moisture matters more than its aggregate volume for terrace viability [3]. Elevation acted as a moderator rather than a direct predictor: its interaction with onset delay was significant ($p = 0.007$), indicating that the same delay produces a steeper TVI decline at higher elevations where soils are thinner and moisture reserves smaller [11]. The phase table reveals that the dominant stressor shifted over time from isolated dry spells in the early period, through onset-driven wall damage in the middle years, to a compound effect involving simultaneous climatic, structural, and labour shortfalls in the most recent phase.

Discussion

The principal finding is that monsoon timing irregularity, rather than total rainfall decline, drives terrace viability loss across the elevation gradient. This aligns with regional analyses by Krishnan and colleagues [2], who reported increased intra-seasonal variability across the Hindu Kush Himalaya, and with Cannon and co-workers [8], who linked western disturbance weakening to more erratic pre-monsoon moisture delivery. The literature agrees that Himalayan agriculture is increasingly rainfall-timing sensitive [5,12], though most earlier investigations lacked the fine-grained TVI metric used here and instead relied on proxy measures such as crop yield alone. Where the present results depart from earlier work is in quantifying the threshold effect. Below a TVI of approximately 40%, field observations showed that terrace walls begin to fail irreversibly: dry-stone masonry collapses during intense bursts, and without timely labour input for repair labour that has often migrated to the plains the damage accumulates across seasons rather than being repaired [4,13]. This non-linear dynamic means that projecting linear trends may underestimate the speed of future viability loss. The phase-wise analysis (Table 2) supports this interpretation: the rate of TVI decline accelerated after 2015, when compound stressors converged. From a practical standpoint, the 40% TVI threshold could serve as a trigger for emergency terrace-rehabilitation programmes, flagging parcels that are approaching irreversibility before the investment required for restoration becomes prohibitive [10,14]. The labour dimension deserves particular emphasis: even where monsoon timing has not yet deteriorated severely, the outmigration of working-age males driven partly by rainfall uncertainty and partly by plains employment opportunities removes the very workforce needed to repair walls after heavy monsoon bursts, creating a compounding vulnerability that purely climatic analyses miss [16]. Integrating labour-availability metrics into the TVI framework in future iterations could strengthen its predictive validity and capture this human dimension of terrace decline.

Limitations

Several constraints bound the interpretation of these results. First, the TVI was assessed cross-sectionally on 90 parcels in 2023 and projected backward using farmer recall for yield and labour inputs, introducing potential recall bias for earlier periods. Second, the six meteorological stations, while covering all three elevation bands, may not capture micro-topographic rainfall variation within narrow valleys. Third, the research did not measure irrigation contributions from gravity-fed channels (guls), which could buffer some terraces against monsoon irregularity. Future investigations should incorporate longitudinal TVI monitoring at annual intervals and explicitly account for supplementary water sources to strengthen the causal inference between monsoon timing and terrace degradation [15].

Conclusion

This research set out to assess how erratic monsoon regimes influence terrace farming viability across three elevation zones in Uttarakhand. The key findings demonstrate that onset delay and mid-season dry-spell frequency explain nearly 80% of viability variance, substantially outperforming total seasonal rainfall as predictors. Terrace viability has fallen below 30% at high elevations and below 45% in the mid-elevation band, with a non-linear acceleration apparent after 2015. For policy, these numbers suggest that a TVI-based early-warning system, monitored annually by block-level agriculture offices and calibrated against real-time monsoon tracking, could identify at-risk terraces in time for preventive wall repair and micro-water-harvesting interventions. Future research should extend the TVI framework to adjacent Garhwal districts, incorporate seasonal forecasting data from the India Meteorological Department extended-range prediction system, and test whether advance warning of delayed onset delivered through mobile-phone-based agro-advisory services can prompt protective management actions at the household level. The integration of labour-availability data into the TVI would further improve its sensitivity to the compound pressures that are now driving terrace decline across the Uttarakhand hill belt, and would provide extension planners with a multi-dimensional screening tool that captures both climatic and demographic dimensions of agricultural vulnerability.

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